MODEL SIMPLIFICATIONS IN ENERGY ASSESSMENT METHODS: SETTING DETERMINISTIC BOUNDARY CONDITIONS FOR FLEMISH SCHOOL BUILDINGS

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ABSTRACT

Building energy assessment methods, used in a regulatory context, impose a calculation procedure under restricted and predefined conditions to check the preset energy performance levels. Standardized boundary conditions and input data are implemented allowing for objective evaluation of various building designs. Focusing on school buildings in particular, these specific boundary conditions are however often inaccurate or even unavailable. Therefore, throughout this paper, typical school characteristics and their uncertainty are studied. The impact on the energy demand calculations is then demonstrated in an uncertainty analysis using the Monte Carlo analysis method combined with the Latin Hypercube Sampling technique. A sensitivity analysis, using the elementary effects method of Morris, reveals the set point temperature, load and users' profiles of lighting and equipment in class rooms as the most dominant input parameters on which additional surveys and questioning are focused to determine possible inaccuracies and to define, where necessary, new, more realistic boundary conditions. As a final result, a list of representative boundary conditions for Flemish schools in particular is determined which can be used directly or can be converted into averaged input data for simplified calculation methods.

KEYWORDS

school buildings; boundary conditions; building energy simulation; Monte Carlo analysis; Latin Hypercube sampling; energy performance

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INTRODUCTION

In Flanders, since January 1, 2006 the 'Energy Performance of Buildings Directive' (EPBD) [1] has been implemented setting ambitious energy performance objectives for all types (residential, office, school, industrial and others) of newly built or (highly) renovated buildings. The evolution towards more energy efficient schools in particular is encouraged by the approval of the 'Directive for Energy Performance in School Buildings' dd.07/12/2007 [2]. In this Directive the minimum required primary energy performance level for schools is defined and the criteria for Flemish passive schools are set.

To check these preset energy performance levels, mainly two energy calculation methods are used: quasi-steady-state calculation methods, which calculates the energy balance in steady-state conditions over a sufficiently long time (i.e. one month) and dynamic methods, which calculates the energy balance with shorter time steps (typically one hour) [4]. The choice between both methods typically depends on the time and expertise available by the (design) team and on the application of the calculations (code compliance checking, design optimization, comfort analysis,…). In Belgium in particular, a compulsory, quasi-steady-state, monthly time-based, single-zone calculation tool (EPB) [3] is applied to judge minimum energy performance requirements in the context of EPBD. To guarantee objective, unambiguous and comparative performance evaluation results, a range of standardized boundary conditions and input data are used for the calculation: deterministic values for operational schedules, ventilation characteristics, internal heat gains,… are defined in the calculation manual [3]. These values are however not always accurate (some semi-empirical data is outdated due to current changes and trends) , realistic (values are sometimes based on information in international standards [4] while real boundary conditions often depend strongly on national or regional) or too general (values are often set for a classification of buildings (eg. non-residential buildings) and are therefore not detailed enough) which might affect the outcome. However, to achieve the goals of the EU Directives, the accuracy and reliability of the assessment results are crucial to ensure the EPB Directive effectiveness. In addition,as the energy assessment calculations are often used during the design process, the calculation results should be as accurately as possible to avoid misleading design decisions and inefficient optimization measures which affect in turn the evolutions and trends on the building market. [Pernigotto2013]

Generally, the impact of input data uncertainties on the accuracy and relevance of the calculation results has been widely studied and has been described in various researches [5, 6, 7, 8, 9]. According to Dewit and MacDonald, [5, 6], default (semi-)empirical parameters and abstractions are a significant factor of uncertainty of energy performance assessment. After all, it is impossible for the (simplified) calculation models to represent exactly the complexity of the use of the building and the underlying physical processes [5, 6]. Similarly, Kim et al. [7] indicated non-realistic model simplifications and assumptions regarding HVAC systems and control strategies as a plausible reason for inaccuracy. Studying non-domestic buildings in particular, Clevenger and Haymaker [8] estimated that due to oversimplification of the modeling assumptions the uncertainty on the energy performance ranges from 10 to 40%. Finally, focusing on school buildings in particular, the authors of this paper investigated previously the impact of implementing more realistic boundary conditions in the quasi-steady-state calculation tools EPB and PHPP [9] for 3 specific case studies [10]. Comparing the calculation results to the results when using the deterministic input data as currently applied in the calculation tools, variations of the annual heating demand from -1.9% to +24.2% in EPB and from +9.4 to +36.9% in PHPP were found. These results show clearly the significant impact of boundary conditions on the heat transfer and heat gain calculations and thus on the final results of the energy building performance assessment.

In conclusion, to obtain objective but realistic energy assessment of a building the deterministic default values and standardized input data used for the energy calculations must be well-considered and specifically adapted to the typology and use of the building.

Several researches on the impact of boundary conditions on building energy performance calculation in residential buildings [11, 12, 13, 14, 15], offices [16, 17, 18, 19] or commercial buildings [11] are found. Research on boundary conditions specifically for (Flemish) schools [20, 8] is however rare. Therefore this study focusses in particular on the (simplified) input of typical school characteristics and their impact on building simulation results. The overall objective is to improve the accuracy of the energy calculations specifically related to the implementation of user's and activity related boundary conditions. Values for (heating) schedules, control systems, use of artificial lighting and equipment, ventilation characteristics, internal heat gains, etc. for schools are studied. Overall uncertainties related to material properties, construction characteristics and weather data are beyond the scope of this study.

Throughout this paper, at first the building simulation model (geometry, building and system properties) which is used for this study is presented. Secondly, the boundary conditions which are studied are summarized. The likely variations of the boundary conditions are then defined by setting their probability distribution functions and ranges based on similar research studies and literature review. Subsequently, these probability functions are assigned to the building model and the responses of the building to the input data perturbations are studied. To that end, an uncertainty analysis (UA) through a Monte Carlo analysis (MCA) is performed. Afterwards, a sensitivity analysis (SA) is done, using the method of Morris, to determine the relative importance of each investigated boundary condition. Once the most dominant boundary conditions are determined, additional surveys and monitoring are performed to gather more realistic and representative data. As the SA is performed prior to the execution of the surveys and questioning, the input data analysis can be performed in a more efficient and less time-consuming way.

Finally, based on the results of the survey and monitoring, a set of deterministic boundary conditions is proposed, which can be used, directly, for dynamic simulations or can be converted into monthly mean input data for the simplified, quasi-steady-state calculation methods. As this work focusses on schools in Flanders in particular, the deterministic boundary conditions which are presented in this paper are only valid for Flemish schools.

1. UNCERTAINTY AND SENSITIVITY ANALYSIS TECHNIQUE

Uncertainty and sensitivity analyses are frequently used for building energy analysis purposes [21, 22, 23, 24]. Various uncertainty and sensitivity analysis techniques can be found. Among all these techniques, one must be chosen specifically appropriate for this research purpose (= parameter identification and factor prioritization). Saltelli [25] distinguishes two overall classes of sensitivity analysis: the local and the global analysis methods. For the local analysis methods the variables or parameters are varied one at a time by a small amount around some fixed point and the effect on the output for each of the parameters is calculated separately. For the global sensitivity method on the contrary, the global effect of all input parameters is studied quantitatively. Previous (more or less) similar research studies show that both the local [16, 14, 5, 13, 12] and the global method - screening-based and regression method [21, 15, 17, 5, 13, 12] - are used for uncertainty and factor prioritization purposes.

For the uncertainty analysis, the global method is selected as it is the purpose to assess the global effect of all investigated boundary conditions. From the global methods, the Monte Carlo Analysis method (MCA) is chosen as it estimates the overall uncertainty in the energy demand calculations due to all the uncertainties in the input parameters regardless of the interactions and quantity of the parameters [6]. The MCA is performed by successively carrying out the following steps: (i) selection of a range and distribution for each input parameter, (ii) sample generation from these distributions, (iii) evaluation of the model for each element of this sample and (iv) performing the uncertainty analysis. For the sample generation the Latin Hypercube sampling technique is used. This sampling technique is more effective compared to random sampling [25] as it ensures full coverage of the whole range of each variable. To that end, the range of the each variable is divided in equally probable intervals and one value is randomly selected from each of these intervals [25]. The sampling is done using the SimLab tool [26].

Focusing on the energy demand in particular, the number of calculations to perform to obtain reliable results of the uncertainty analysis, is independent of the number of input parameters [27, 6]. According the same researches [27, 6], 80 simulations suffice for each building model (§2) to assess to impact of the investigated parameters.

Although the MCA method can also be used for sensitivity analysis purposes, the local sensitivity analysis technique of Morris is chosen for sensitivity analysis purposes. After all, the indicators for sensitivity used in the MCA method assume near-linearity of the model. As however variable independency and linearity of our model cannot be guaranteed, the screening method of Morris, also referred to as the one-variable-at-a-time (OAT) method [28], is chosen as the alternative.

The Morris method can be characterized as a screening method with global characteristics [25]. The global sensitivity is considered as the influence of the whole range of variation of the input parameters, X, which is described by a probability distribution, F_i . By varying the input parameter set, the 'effect' of each 'element' is then calculated as:

$$EE_i = \frac{Y(X_1, X_2, \dots, X_{i+\Delta}, \dots, X_k) - Y(X_1, X_2, \dots, X_k)}{\Delta} \quad (1)$$

Two sensitivity measures, μ and σ , which are respectively the estimates of the mean and the standard deviation of the distribution, F_i , of the elementary effects, are used to assess the sensitivity of each investigated parameter [29]. Campolongo et al. [30] proposed adding the use of μ *, which is defined as the estimate of the mean of the distribution of the absolute values of the elementary effects. The regular mean, μ , has the drawback that if the distribution, F_i , contains negative elements, some effects may cancel each other out when the mean is computed.

2. BUILDING SIMULATION MODEL

2.1. BUILDING DESCRIPTION

A large variety of schools is found [32]. After all, specific space requirements for class rooms, corridors, sanitary and technical rooms are found depending on the educational form (from general to vocational education) and the age of the students (from nursery to secondary education) resulting in a large diversity of school buildings. To guarantee representative results of our study, a representational school building model is used which abstracts and simplifies real architectural data and typical characteristics (Figure 1) [33].

To define the building model, the representative type model approach is used . This approach attempts to represent the investigated school building stock by using a fictional but realistic, prototypical building model based on averaged values [71]. To obtain accurate and realistic information on current school architecture (averaged floor surface areas, typical heights, dimensions and space type profiles), a selection of 35 schools is chosen from the extensive database of Flemish school characteristics of the Agency for School infrastructure (AGIOn). To ensure statistical accuracy of the survey, the selected buildings are spread over the Flemish region and all educational forms are equally covered. To incorporate current trends and changes (e.g. more stringent energy performance requirements [1]), the selection is restricted to current building practice (constructed after 2005) only.

A rectangular building model with a central corridor is used as it is still the most common built form of schools [66]. The building size of the model is based on the 'Physical and Financial Standard of the Flemish Government' [67]: the gross surface area is calculated as 1495 m² + 6,9 x (number of students minus 165) increased with 485 m² additional space bound for sports activities and physical education. For an occupancy of 250 students on average, this results in a total gross surface area of 2567 m². The width of the building is based on the presence of a corridor (1.8m width [47,68]) with a class room at both sides (width 6m [69]). The façade length is restricted to 90m maximum based on Flemish building fire safety legislation. This results in a two storey building model. The net free floor height is set to 2.8 m.

For the space type profile of the schools, the type of the rooms, the occurring number of each type of room and the surface area of more than 2000 rooms is measured and listed. To limit the complexity of the representational models, only those space types are included which occur in more than 50% of the investigated schools [70]: classrooms (41.1% → 845.9 m²), a teacher's room (≈ meeting/seminar room)(3.1% → 63.3 m²), offices (5.2% → 106.4 m², a gym (13% → 264.8 m²), a canteen and kitchen (11.5% → 235.5 m²), circulation zones, sanitary and storage rooms (26.4% → 542.5 m²). The architectural plan is shown in Figure 1. Detailed architectural model information can be found in Table 1 and Table 2.

Insert Figure 1

Insert Table 1

Insert Table 2

As the impact of the boundary conditions might differ in relation to the energy efficiency level of the building envelope [35], two building variants are used ranging the global insulation level discretely between an upper limit (= the 'base case' variant representing current (newly built) schools according to the Flemish EPBD dd.2014, U_{mean} = 0.34 W/(m²K)) and a lower limit (= the 'best practice' variant, U_{mean} = 0.17W/(m²K)). The 'base case' variant is equipped with a simple extraction ventilation system. The 'best practice' variant has a balanced mechanical ventilation system provided with an air-to-air heat exchanger with an efficiency of 75%. The supply of air is provided into the constantly occupied rooms (e.g. class rooms, gyms, offices). The operation of the fans is controlled by a time schedule according to the operational profile. The heating (October - May) and cooling is provided by an all-air system. During night-time, weekends and holidays a setback temperature of 12 °C and 30 °C is assumed for heating and cooling respectively. A simplified shading device control strategy ($q_{control}$ = threshold of total solar radiation on the surface when blinds are closed or opened = 150 - 250 W/m² (dead band)) for the retractable shading device is implemented. In case the blinds are closed, 70% of the total solar radiation on the shaded surface is blocked. North-facing windows are not provided with an external shading device. As most schools in Flanders have massive structures (heavy external and internal walls, roof and floor - C m = 7.27 * 10^8 J/K), only this construction type is considered for the study. An overview of the composition of the opaque building elements is given in Table 3.

Insert Table 3

2.2. BUILDING ENERGY ASSESSMENT TOOL

Although the calculation process is not completely in line with the quasi-steady-state calculation methods, the impact of input data variability is studied using the dynamic multi-zone building energy simulation program TRNSYS 17 [36]. After all, in accordance with the technical Standard EN ISO 13790, dynamic simulation tools can be employed for refining the steady-state methods. As dynamic phenomena (i.e. climatic data, time schedules) and numerical values (occupant density, internal heat gains) can be implemented in a more realistic way compared to the quasi-steady-state method, this simulation tool is more suitable for this research. To guarantee comparability of the dynamic and static calculations however, the procedures as described in EN ISO 13790 regarding the implementation of standardized boundary conditions to guarantee consistency with the monthly methods, have been respected.

The building is modeled as a multi-zone (seven zones) building based on different orientations and users' profiles of the rooms. The zone 'class F' (1571 m^3) comprises all class rooms at the front of the building. The zone 'class B' (797 m^3) contains all class rooms at the back of the building. The rest of the building consists of a canteen/kitchen (659 m^3), a gym (1553 m^3), offices (298 m^3), a teachers' room (177 m^3) and space for circulation, sanitary and storage (1515 m^3) as shown in Figure 1. Time schedules, user's profiles and heating patterns that differ in time are implemented for each zone separately.

The thermal behavior is studied with a time step of 15 min. A typical weather data set for Uccle, Belgium, derived from measured meteorological data by Meteonorm is used. The generation of the various files is done in MATLAB automatically coupling the input data to the TRNSYS tool.

The output considered is the energy demand for heating and cooling.

2.3. Activity and users' behavior related boundary conditions

This section discusses the physical background and the uncertainty interval of the input data related to the typology and the use of schools. Typical ranges and distribution functions for (heating) schedules, control systems, use of artificial lighting and equipment, ventilation characteristics and internal heat gains for schools are set. Depending on the type and source of uncertainty (systematic or random error), a specific but representative probability distribution function for each of the investigated boundary conditions is chosen. According MacDonald [6], uniform functions are mostly suitable for modeling systematic errors. Normal distribution functions are mostly appropriate for measured physical data e.g. temperatures. Log-normal functions are used combining two or more normally distributed parameters (e.g. infiltration rate, metabolic rate) and triangular functions are highly suitable to describe varying parameters with a clear minimum, maximum and most likely value (e.g. occupant density rate). As the influence of the distribution function is less important than the range [31] and as it is the objective of this paper to model the impact of model simplifications (= systematic errors), uniform distribution functions are used for all boundary conditions for which no specific data is found [6].

In general, accurate (empirical) data of the variability of boundary conditions is rare. Empirical and experimental information of typical school characteristics is even more difficult to find. In addition, input data related to occupancy and activity specifically are difficult to set and thus highly uncertain [6]. As a result, the range of the parameters used for the UA and SA are mainly based on literature and values obtained from comparable research studies for other types of buildings.

Operational schedule: In Flanders, the school year starts on 1 September and ends on 30 June. From 1 July up to 31 August the school is closed due to summer holidays. Lessons are evenly spread over five days from Monday to Friday. Generally, a school day starts at 8h30 and ends at 16h. Wednesday afternoon is free. A total of 37 days off are taking into account in addition to summer holidays and weekends: 5 days in January, 3 at the end of February and 2 at the beginning of March, 12 in April, 3 in May, 1 in June, 3 in October, 2 in November and 6 in December. This schedule results in ± 1200 annual operating hours on average.

Although school opening hours are generally similar, small differentiations between schools or rooms are observed due to e.g. outdoor meetings/classes and breaks.These variations of the operational schedules result in a change of the control of the HVAC system, lighting and equipment. Additionally, they might lead to a different occupancy and thus possibly affect both internal heat gains and ventilation rates. The possible variations of the operational schedules can be considered using the relative absence factors (RA). In conformity with DIN V 18599 [39], the relative absence is introduced as the factor which accounts for part-time operation during a usage day: 25% for the class rooms, 30% for offices and 50% for teachers' rooms. No relative absence is assumed for the gym and canteen. As no further data on range and distribution for the relative absence factors are found, values are uniformly varying between ± 10% [6]. The results are summarized in Table 3.

Set-point temperature, °C: Schools typically have strongly discontinuous users' profiles and accordingly intermittent heating patterns. Specific data on (set-point or (monthly) averaged) room temperatures are found in (inter)national standards and technical reports. Some standards focus on the design criteria and dimensioning of the heating and - if present - the cooling plant (e.g. EN 15251 [40], EN 12831 [41]). Others are used for energy calculation purposes (e.g. EN ISO 13790 [4], DIN V 18599, NEN 7120 [42]). In addition, various standards (EN ISO 7730 [43], ASHRAE [44]), regulations and guidelines focus on the minimum requirements for thermal comfort and indoor temperature set-points in general, or in schools in particular [45, 46, 47]. As in this specific study, dynamic simulations are used to check the impact of varying temperatures on the energy demand, set-point temperature variations, are investigated. The conversion of these set-point temperatures to monthly mean indoor temperatures which can be implemented in the quasi-steady-state calculation method is beyond the scope of this study and will be discussed in future work.
Due to the significant difference in (winter) comfort requirements in gymnasia or sport halls, temperature set-points are defined for two separate room categories: (i) room with a sports function and (ii) all other rooms. The ranges of the set-point temperatures are based on the lower and upper

limit of respectively the lowest and highest thermal comfort class as defined in ISO 7730, EN 15251 and [46]. On the contrary, a single set-point for cooling is used for all rooms (25°C) [40]. Due to the physical nature of the parameter, a normal distribution function is mostly appropriate [6] (Figure 2). Although the set-point temperature range and the distribution function are set equal for most of the rooms (except the gym in case of heating), different set-point temperature variations are set for each zone separately. This allows on the one hand the simulation of the effect of limited inter-zonal temperature control differences. On the other hand, as all other parameter variations are defined for each zone separately, potential overestimation of the impact of the set-point temperature is avoided.

Insert Figure 2

Occupant density, m^2 /pers: Variations of the occupant density affect both the internal heat gains and the ventilation flow rates. Various standards can be found specifying occupant density rates for specific room types. Some are used in the framework of energy calculations (NEN 7120, DIN V 18599), others are used to calculate the ventilation rates which are necessary to assure good indoor air quality (EN 13779). According to [6], a triangular distribution function is mostly appropriate to describe occupancy variations. The minimum, maximum and most frequent values (modes) for the various room types are set based on the aforementioned standards. Results are summarized in Table 3.

Ventilation rate, m^3 /(pers.h): The Flemish EPBD [3] requires at least a moderate indoor air quality (IDA 3 - EN 13779 [48]). On the other hand, to minimize the ventilation and related energy losses, installed ventilation rates in schools are often limited to the absolute minimum required. Therefore the considered variations of the ventilation rates are restricted to IDA3 class only. The mean ventilation rate is set equal to the default value for IDA3 as found in EN 13779. To assess the sensitivity, hygienic air flow rates are uniformly varying ± 10% these default values [49].

Internal sensible heat gains, W/pers or W/m^2 : this study focuses in particular on the uncertainty of the internal heat gains related to the typical use of schools (i.e. installed lighting and equipment load intensities). The actual sensible heat emission of people, equipment and lighting is beyond the scope of this research.

(i) Occupant, W/pers: values for the sensible heat gain due to occupants are found in DIN V 18599 and are adapted to the Flemish school system. As the heat gains due to occupants are related to age, values are set for children (students of elementary schools, < 12 years old - 60 W/pers) and (young) adults (teachers, students of secondary schools, > 12 years - 80 W/pers) separately. As variations in sensible heat emission are not accounted for in this study, variations of the heat gains are exclusively related to possible changes of the occupant density which are discussed previously.

(ii) Equipment, W/m² : the source of uncertainty of load intensities is mostly related to the specifications and usage of the equipment. According to [29] triangular probability distribution functions are mostly suitable. The minima, maxima and modes are based on DIN V 18599 and NEN 2916 [50]. For those boundary conditions for which no further information is found, the ranges are set to be ± 10% [6] (Table 3).

(iii) Lighting, W/m² : lighting is modeled for each space as a function of the requested illuminance (EN 12464 [51]) and the installed lighting power. The upper limit is set equal to the minimum required normalized power density, NPD, in class rooms (= 2.5 W/(100lux.m²)) [52]. The lower limit (= 1.5 W/(100lux.m ²)) is based on the guidelines for low energy non-residential buildings [53]. A triangular distribution function is assumed [6].

As equipment and lighting are only part of the occupied time in use, a partial operational time factor (POF) is introduced. The factor is calculated as the time while equipment or lighting are effectively used to the total operational time. Reference values are found in DIN V 18599 and are summarized in Table 3 for the various school zones.

An overview of the investigated boundary conditions including the range and the characteristics of the probability functions is given in Table 4.

Insert Table 4

3. RESULTS

3.1. UNCERTAINTY ANALYSIS

Firstly, the results of the MCA are discussed. The uncertainty on the heating and cooling demand is shown in Figure 3 for the 'base case' and 'best practice' variant separately. A histogram and cumulative normal distribution function are used to show the variance of the output (energy demand) due to perturbations of the investigated boundary conditions as set in Table 4. As the cooling demand in the 'base case' variant is practically non-existing (maximum 0.4 kWh/(m².a)), only the heating demand is discussed for this building variant.

Insert Figure 3

Given the large number of simulations, the uncertainty of the output of the MCA can be expected to be normally distributed, independent of the probability distributions which are used for the input data [54]. The normality plots, shown in Figure 4, confirm a Gaussian distribution of the output results. It can therefore be guaranteed that 95% of the variations of the output are found in the confidence interval defined as the mean plus and minus two times the standard deviation. For the 'base case' variant this results in a 95% confidence interval of 49.2 ± 6.9 kWh/(m².a) or a spread of ± 14.1% for the heating demand. Similar results are found for the 'best practice' variant. The impact on the heating demand is slightly higher but in the same order of magnitude with a spread of 15.1% or a 95% confidence range of 11.5 ± 1.7 kWh/(m².a) . The impact on the cooling demand is 27.9% or 5.1 ± 1.4 kWh/(m².a).

In conclusion, the results of the UA emphasize the impact of the boundary conditions on the energy demand calculations concluding there is a need for an accurate estimation of the implemented boundary conditions.

Insert Figure 4

To check the robustness of the results of the UA, the impact of the varying boundary conditions on the energy demand is studied for some extra building variants. To that end, two extra building characteristics are varied between an upper and lower limit (the window to wall ratio WWR = 20 -

40% and the thermal capacity heavy - light structure) and the impact on the results of the UA is studied. As shown in Table 5, the impact of the building characteristics is limited (<2%). Approximately similar results of the UA are obtained for all building variants.

Insert Table 5

The variations of the uncertainty are ± 0.4% and ± 1.8% for the 'base case' and 'best practice' variant. Further diversification of the building model based on construction and architectural characteristics is therefore not necessary for this specific research objective.

3.2. SENSITIVITY ANALYSIS

The sensitivity of the energy demand due to each of the investigated boundary conditions is determined by the mean, $\mu*$, and the standard deviation, σ , of the elementary effects. A high mean, $\mu*$, indicates a large sensitivity. A high value of σ implies that the value of the elementary effect is strongly affected by the choice of the other factors' values or that the factor is nonlinear [29]. If both $\mu*$ and σ are low, the investigated parameter is negligible.

The results of the SA are shown for the 'base case' (heating demand only, Figure 5 (a)) and 'best practice' variants (heating, Figure 5 (b), and cooling demand, Figure 5 (c)).

Insert Figure 5

To maintain clarity of the figure, only the 5 most influential parameters (covering 65 to 75% of the variations) are named: the operational schedule (i.e. relative absence, RA_{class}), the set-point temperature for heating and cooling ($\theta_{i,heat/cool,class}$) and the use of equipment and lighting (internal heating gains (IHG) and partial operational time factor (POF)). These boundary conditions have the highest impact on the energy demand calculations and have the highest σ .

Although small differences are found (Figure 5) between both building variants on the one hand and between heating and cooling demand on the other hand, the main trend is similar. In general, the operational schedule and related occupant attendance and users' profiles can be considered as the most dominant parameters followed by the set-point temperature for heating/cooling. Similar results were found by Demanuele et al. [20] and Clevenger et al. [8]. Both researchers emphasize the substantial impact of the highly variable and unpredictable occupant' behavior on the energy performance in schools.

Moreover, all the dominant boundary conditions are related to the use of class rooms. The boundary conditions related to the other school zones (e.g. canteen, offices) are less important. As class rooms cover more than 40% of the total surface area (§2), the use and occupancy of these specific rooms clearly dominate the energy demand of the building.

To analyze the averaged elementary effect on the heating demand (kWh) for both building variants in detail, an overview of the 10 most dominant boundary conditions is given in Figure 6. To compare the data, the relative mean elementary effects (%) are used, defined as the ratio of the mean to the sum of all averaged elementary effects.

Insert Figure 6

Overall, the relative absence factor for class rooms ($\mu*$,% is 36% and 29% for the 'base case' and 'best practice' variant respectively) has the largest impact on the energy demand. Furthermore, when comparing the results of both building variants, the occupant density is much more significant for the 'base case' variant. Due to the implementation of a heat recovery device in the 'best practice' variant, much lower ventilation losses occur. As ventilation rates are set in relation to the occupant density, this boundary condition is much less important in the 'best practice' variant. Furthermore, the overall impact of the set-point temperature for heating is slightly higher for the 'base case' variant ($\mu*$,% is 17% compared to 16%). Due to the lower energy efficiency level of the building envelope (U_{mean} = 0.43 W/(m²K) vs. U_{mean} = 0.17 W/(m²K) , n_{50} = 3 h^{-1} vs. n_{50} = 0.6 h^{-1}), variations of the set-point temperature lead to larger changes of the heat losses which in turn affect the heating demand. Conversely, for the 'best practice' variant, the impact of the internal heat gains due to lighting and equipment (partial operation) is more important. As the heat losses are generally lower, a larger part of the heating demand is covered by the internal heat gains. As a result, the highly insulated buildings are more sensitive to changes of the internal heat gains.

In conclusion, based on the outcome of the SA, extra field data on operational schedules, set-point temperatures, occupant density rates and the use of equipment and lighting in class rooms in particular are collected.

3.3. SETTING DETERMINISTIC BOUNDARY CONDITIONS

The objective of this section is to capture possible inaccuracies of the implemented boundary conditions by comparing the values in Table 4 to real field data and monitoring results of (Flemish) schools. To limit the workload, the collection of the field data is however limited to the most influential boundary conditions as revealed by the SA. Specifically, deterministic user's schedules and heating patterns of school buildings are based on (i) a site-visit and detailed survey of 20 recently built or highly renovated schools in Flanders, and (ii) on a questioning of a much larger sample of schools (981 were contacted of which 8% responded) [57]. Data on the occupancy is collected by a large-scale questioning: 144 schools were contacted of which 12.5% responded [58]. In both questionings, the contacted schools are spread over the Flemish region and both elementary and secondary schools are included to ensure statistical accuracy of the survey.

For less influential boundary conditions no extra survey data is collected. These deterministic values are set equal to either the averaged value or mode of the distribution functions as defined in Table 4.

Operational schedule: in schools, the general operational schedules and related attendance of the occupants are well predictable [35]. Accordingly, survey results show that, although schools can freely decide on the exact starting and closing time, most of the schools (73% to 81%, depending on the typology) implement the official operational schedule [57]. The other 20% to 25% of schools starts and closes either 0.5 hour earlier or 0.5 hour later. As these differences are however very limited, no changes to the regular school opening hours are suggested.

In addition, the relative absence factors are set. For class rooms, daily play breaks (15 minutes, one in the morning and one in the afternoon), outdoor classes and excursions must be accounted for. As however the outdoor classes are limited (sports class – 2 hours per week) and extra excursions are only occasional, the RA_{class} as used for the UA and SA (25%) underestimates largely the real use of the class rooms. Therefore, the RA_{class} is changed to 12.5% (two daily (15 min) play breaks and 2 hours of outdoor classes per week). Values for offices and teachers' rooms are not changed and can be found in Table 4 (RA_{office} = 30%, RA_{teach} = 50%). The resulting deterministic daily occupancy profiles for the various school zones are summarized in Figure 7, with the exception of Wednesday afternoon, which is free.

Considering the significant impact of the operational schedule and related occupancy (see results SA) on the energy demand calculations, the possible occurrence of after school activities is investigated. Survey results show that in 70% to 80% of the investigated cases, extra classes and after school activities are organized [57]. However, according to the same survey results, these extra after school activities and related school zone occupancies vary considerably (either daily, weekly or only occasionally) between schools [57]. In addition, the related extra school opening hours vary substantially from 0.5h up to 5h. In some exceptional cases, the schools are opened during the weekends. In contrast, after school activities (and related heating (and air conditioning) schedules) are generally (± 65%) restricted to a small part of the building (a single class room or gym only). Taking in mind the diverse and uncertain character of the after school activities, they are not included in the deterministic set of boundary conditions.

Insert Figure 7

Set-point temperature, °C : for each of the investigated schools, the heating schedules are documented and (heating) set-points temperatures are listed for both room categories (gym and all other rooms). Results are shown in Figure 8.

Insert Figure 8

As shown in Figure 8, secondary schools have a slightly more stable but somewhat lower temperature regime. Especially nursery schools which accommodate young children (< 6 years old) request slightly higher indoor temperatures (21-22°C). The majority (95%) of the visited elementary schools has a set-point of 21 ± 1°C, 85% of the questioned secondary schools has a set-point temperature of 20.5 ± 0.5°C. Accounting for this information, the deterministic set-point temperature for heating is set equal to 21°C for both educational forms.

For sports halls and gymnasia, the survey reveals a set-point temperature variation between 12°C and 20°C, with the median equal to 17°C which is equal to the mean temperature as used previously in the UA and SA (see Table 4) and therefore used as the deterministic value.

Schools in Flanders generally do not have a (active) cooling system. Only in exceptional cases, active cooling is provided in restricted zones with extremely high internal heat loads such as server rooms. Real data on set-point temperatures for cooling is therefore hard to find. As a result, the set-point temperature for cooling is set equal to the average value as used in the UA and SA, i.e. 25°C (Table 4).

Occupant density, m²/pers: the occupant density rate is determined as the mean available surface area per student (m²/pers). Therefore, data on both the number of students and the surface area of regular class rooms are collected [58]. The variability of the class room surface area is determined based on the same sample as used for the definition of the representational building model schools: the surface area of approximately 1500 rooms is measured and listed. The data on occupancy is collected by a questioning (144 schools were contacted, 12.5% responded). In total, the number of students in 92 classes is collected. The survey reveals a median of 3.0 m² /pers. Assuming an average surface area of 57 m² for class rooms [58], this results in 19 students per class on average which is comparable with recent data gathered from Flemish elementary schools by Stranger et al. [59].

Finally, an extra absenteeism percentage is defined to account for the possible nonattendance of pupils (e.g. due to illness) as it affects the actual occupant density which in turn influences the internal heat gains and ventilation losses in case demand-controlled ventilation systems is assumed. The same sample of buildings is used [58], however only 39 schools responded. Results reveal an average absenteeism percentage of μ = 5.9%. Comparable results (= 6%) are found in a survey of Norwegian primary schools where the actual occupant density and time-of-use were registered and measured [60].

Internal heat gains due to equipment, W/m² : Information on the use and occurrence of equipment in schools is based on questioning, using the same sample of schools as used for set-point temperature determination [57]. In addition, available large-scale databases on energy consumption and load profiles in schools [55, 56], including detailed information on Flemish schools, are studied. All survey results reveal an increasing trend in electronic equipment availability in schools the last decade. A

European study showed that the number of available computers per student raised from one for every 20 students to one for every 4 students between 2000 and 2009 [56]. A similar, yet slightly less increasing, trend is noticed in Flanders [55]: ± 18 desktops, laptops, tablets and e-readers are available per 100 students. Despite the growing use of electronics in class rooms, (extra) heat gains remain limited due to the introduction of more efficient technology. Focusing mainly on the use of computers, an internal heat load of 5W/m² (= ± 6 students per computer (80 W per computer) which results in ± 4.8 W/m² on average) is set as the deterministic value.

Concerning the exact use of equipment, detailed monitoring results are restricted. Therefore, examplementary schedules for equipment loads in class rooms which are used in other energy performance calculation methods [61, 62, 63] are used as a reference (Figure 7(b) – marked in grey lines). All assume a relative high use of equipment during the opening hours of the school (70 up to 100%). However, monitoring results of the use of ICT in Flemish schools [55] show that the use of computers in class rooms is limited: only 3.1% of the students uses the computer daily, 30.1% uses the computer only a couple of times a year. Detailed information on the exact time of use is however not available. Consequently, the value as found in NEN 2916 (partial operational time factor of equipment in class room = 15 %), is used as the deterministic load profile (Figure 7(b) – marked in red line). Combining the partial operation time factor of 15% with the internal heat load as set previously, a time-weighted averaged $IHG_{equipment}$ of 1 W/m² is obtained which is again in conformity with the averaged value as found in standard NEN 2916.

Internal heat gains due to lighting, W/m² : the internal heat gains due to lighting are calculated as the product of the requested lighting comfort requirements and the installed normalized power density (NPD). In most class rooms however board lighting is used requiring some additional vertical luminance too. Consequently, the NPD value is only applicable for areas where a uniform luminance is required over a task area approximately equal in area to the floor and is therefore not really suitable for class rooms [64]. The target power load, a parameter which is generally used in Flanders as a criteria for granting (re-)lighting, would be more suitable to use in the deterministic model. Ryckaert et al. [64] developed a method to calculate this target power load in function of the number of annual usage hours (± 1200h), the lighting system efficiency (> 90 lum/W), the efficiency of the luminaires

(90%), the maintenance factor (0.85) and a surface area of the 'work zone' of a class room equal to 42.7 m² as prescribed in [65]. For class rooms this results in an installed lighting load, $P_{T,light,class}$, of 10.6 W/m².

Concerning the lighting profiles in class rooms, again exact monitoring results are unavailable. Schedules for manually (Figure 7(c) – marked in grey full lines) or automatically controlled lighting (presence detection, IR - Figure 7(c) – marked in grey dashed lines) as found in similar calculation methods [61, 62] are used as a reference. Accordingly, both a manually (18% base load assumed [61]) and a time controlled (no after hour usage assumed) lighting load profile are set for the deterministic model (Figure 7(c) – marked in red lines). Due to the strong building case-specific characteristics, daylight control of lighting is not considered as a deterministic boundary condition. Both control systems assume constant use of lighting whenever the class is occupied.

Additionally, after hour usage of equipment and lighting, not specifically related to any school activity, cannot be neglected. Whereas students' attendance can be easily set equal to the occupancy schedule, this is not the case for equipment as the after hour operation is much harder to predict. As a result a base load is introduced for the equipment (Figure 7(b) – marked in red line) and manually controlled lighting systems (Figure 7(c) – marked in red full line), implying that part of the daily heat gains remain present during the nights and weekends. Due to lack of real data in Flemish schools, the values (= 5% for equipment (NCM) [63] and lighting [62]) are set equal to plausible values as found in literature.

An overview of all the deterministic values for all the activity and operational related boundary conditions is given in Table 6.

Insert Table 6

To conclude, a comparison is made between the results of the UA and the annual energy demand calculations using the newly defined boundary conditions ($Q_{H,new}$ /$Q_{C,new}$ - Table 7). In addition, monthly energy demand calculations using both the averaged values according Table 4 (see Figure 10 original) and the newly defined boundary conditions according Table 5 (see Figure 10 - new) are compared. Results are shown in Figure 9 and Figure 10 respectively for the 'base case' ($Q_{H,base}$) and 'best practice' variant ($Q_{H/C,best}$).

Insert Figure 9

Insert Figure 10

Insert Table 7

As shown in Figure 9, the implementation of the new boundary conditions leads to a larger deviation of the heating demand compared to the average result of the UA for the 'base case' variants. For the 'best practice' variants however, a closer fit to the average result is found. Additionally, both Figure 9 and Figure 10 demonstrate that matching the boundary conditions to the typical use and characteristics of school buildings results in a raise of the heating demand, $Q_{H,nd}$, and a drop of the cooling demand, $Q_{H,nd}$. The relative impact is slightly higher as the energy efficiency level of building increases. In real terms, the annual heating demand of the 'best practice variant' rises from 11 kWh/(m².a) to 12 kWh/(m².a) (= + 8%). Taking in mind the strict criteria for passive school buildings (annual heating demand ≤ 15 kWh/(m².a) [2]), this raise is significant. As a result, the introduction of the new boundary conditions as defined in this paper in the obligatory energy assessment tool (EPB), affects the outcome and in turn might affect final designs of real school buildings.

CONCLUSIONS

Building energy assessment methods, used in a regulatory context, impose a calculation procedure under restricted and predefined conditions to check the preset energy performance levels. Standardized boundary conditions and input data are implemented allowing for objective evaluation of the building design. Preset values for (heating) schedules, control systems, use of artificial lighting and equipment, ventilation characteristics, internal heat gains, … are defined in the corresponding calculation manuals. These values are however sometimes inaccurate, unrealistic or too general, which affects the outcome of the calculation.

An uncertainty analysis reveals a spread of 15.15 kWh/(m².a) or more than 30% of the annual heating demand in less energy efficient building variants (‘base case’) due to likely variants of the input data. For better insulated buildings (‘best practice’), the annual heating and cooling demand vary up to 4.1 kWh/(m² .a) or ± 35% and 4.3 kWh/(m² .a) or ± 89% respectively. These results show clearly the (relative) uncertainty or inaccuracy of the assessment results arising from the implemented input data and assumption made by the calculation method. These results are particularly interesting for setting further fine-tuning objectives of the method or when using the calculation method for energy performance compliance checking, especially for passive buildings and/or net zero energy buildings which need to comply with (very) strict energy performance requirements. In addition, as energy assessment tools are often used for design decision support and optimization processes, assessment results should be accurate to avoid misleading design decisions and optimization steps. Therefore to guarantee assessment results that fit reality, boundary conditions are redefined to approach real conditions more accurately and are adapted to the use and typology of the building based on collected field data and monitoring results. To limit the according workload, a sensitivity analysis is performed priory through the local method of Morris, revealing the users’ and load profiles, comfort settings and the occupant density rate of the class rooms as the most dominant parameters. Based on the collected data, set-point temperatures for heating (17°C in gym, 21°C in all other rooms) and cooling (25°C) are set as the standard. The occupant density rate is set equal to the median of the survey results (3m² /pers). The internal heat gains due to lighting are now calculated using the target power load $P_{T,light,class}$ = 10.6 W/m² instead of the normalized density power as currently used. Finally, an after hour use of 5% is suggested for equipment and manually controlled lighting systems.

As a final a set of representative boundary conditions is obtained which can be used, directly, for dynamic simulations or can be converted into monthly mean input data for the simplified calculation methods in the context of energy compliance checking. Focusing on school buildings in Flanders, the results are however specifically valid for Flemish schools only. As building characteristics depend strongly on local customs and building typology, they cannot be generalized. The general results confirm however the requirement for reevaluation and specification of the boundary conditions used in the calculation method. The research approach as described in this paper can then be used as a reference for improvement of the simulation code for other building types and/or for other regions and countries.

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FIGURE CAPTIONS

Figure 1: Rectangular shaped floor plan with middle corridor, a representational building model for schools.

Figure 2: Normal distribution (full line), cumulative normal distribution (dashed line) and mean values (dotted line) of the set-point temperature for heating for various school room types.

Figure 3: Uncertainty of the annual heating and cooling demand for both the building variants: histogram and cumulative normal distribution function.

Figure 4: Normality plot for normal distribution of the energy demand, kWh/(m².a).

Figure 5: Morris sensitivity measures $\mu*$ and σ of the energy demand, kWh for varying boundary conditions (only the five most important factors are named - logarithm scale)

Figure 6: Morris sensitivity measure $\mu*$ (%) of the heating demand for the 10 most influential boundary conditions of both building variations.

Figure 7: Comparative literature study of the operational schedule for a typical class room. The deterministic user's profiles for occupancy (a), equipment (b) and lighting (c) are marked in red. Regular school openings hours are marked in light blue.

Figure 8: Survey results: heating set-point temperature in elementary and secondary schools.

Figure 9: Implementation of deterministic boundary conditions on the annual heating ($Q_{H,nd}$) and cooling demand ($Q_{C,nd}$): comparison with the results of the uncertainty analysis (box plots graphically illustrating the minimum, the lower quartile, median, upper quartile and maximum heating/cooling demand)

Figure 10: Impact of the implementation of boundary conditions on the monthly heating (marked in red) and cooling (marked in blue) demand for two different school building models.